Examination of Current and Future Permafrost Dynamics Across the North American Taiga-Tundra Ecotone

Bradley Gay[1,2], Amanda Armstrong[2,3], Batuhan Osmanoglu[2], Paul Montesano[2], Kenneth Ranson[2], and Howard Epstein[3]

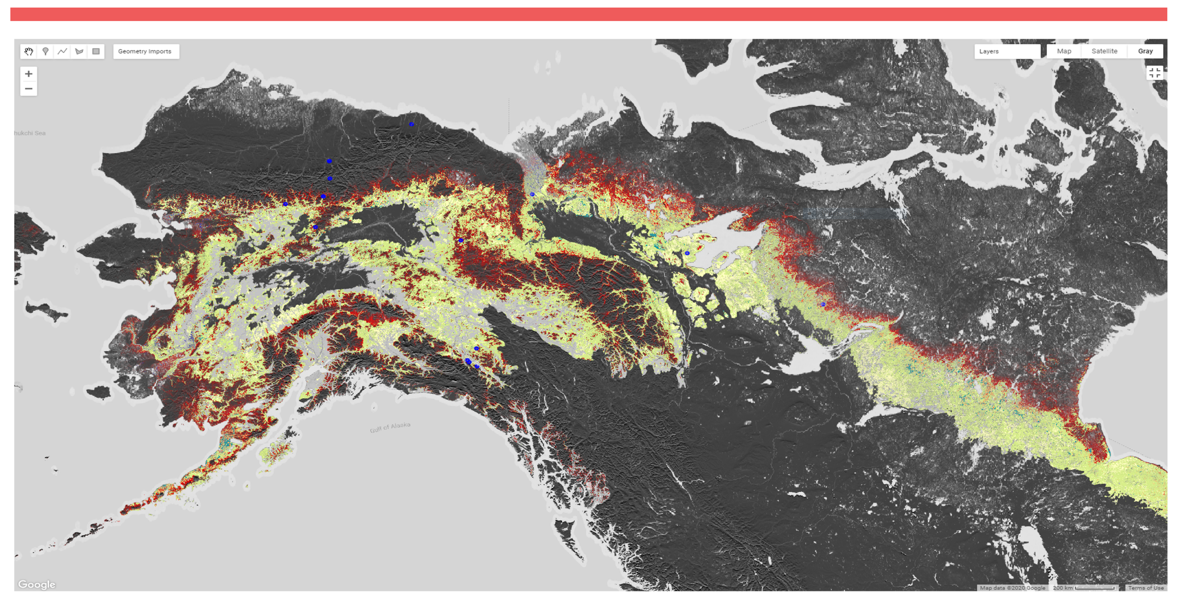
[1]George Mason University, Department of Geography and Geoinformation Science, USA; [2]NASA Goddard Space Flight Center, Biospheric Sciences Laboratory (Code 618), USA; [3]University of Virginia, Department of Environmental Sciences, USA

ARCTIC – BOREAL VULNERABILITY EXPERIMENT

Abstract

In the Arctic, the spatial distribution of boreal forest cover and soil profile transition characterizing the North American Taiga-Tundra Ecological Transition Zone (TTE) is experiencing an alarming transformation. The SIBBORK-TTE model provides a unique opportunity to predict the spatiotemporal distribution patterns of vegetation heterogeneity, forest structure change, arctic-boreal forest interactions, and ecosystem transitions with high resolution scaling across broad domains. Within the TTE, evolving climatological and biogeochemical dynamics facilitate moisture signaling and nutrient cycle disruption, i.e., permafrost thaw and nutrient decomposition, thereby catalyzing land cover change and ecosystem instability. To demonstrate these trends, in situ ground measurements for active layer depth were collected to cross-validate below-ground-enhanced modeled simulations from 1996-2017. Shifting trends in permafrost variability (i.e., active layer depth) and seasonality were derived from model results and compared statistically to the in-situ data. The SIBBORK-TTE model was then run to project future below-ground conditions utilizing CMIP6 scenarios. Upon visualization and curve-integrated analysis of the simulated freeze-thaw dynamics, the calculated performance metric associated with annual active layer depth rate of change yielded 76.19%. Future climatic conditions indicate an increase in active layer depth and shifting seasonality across the TTE. With this novel approach, spatiotemporal variation of active layer depth provides an opportunity for identifying climate and topographic drivers and forecasting permafrost variability and earth system feedback mechanisms.

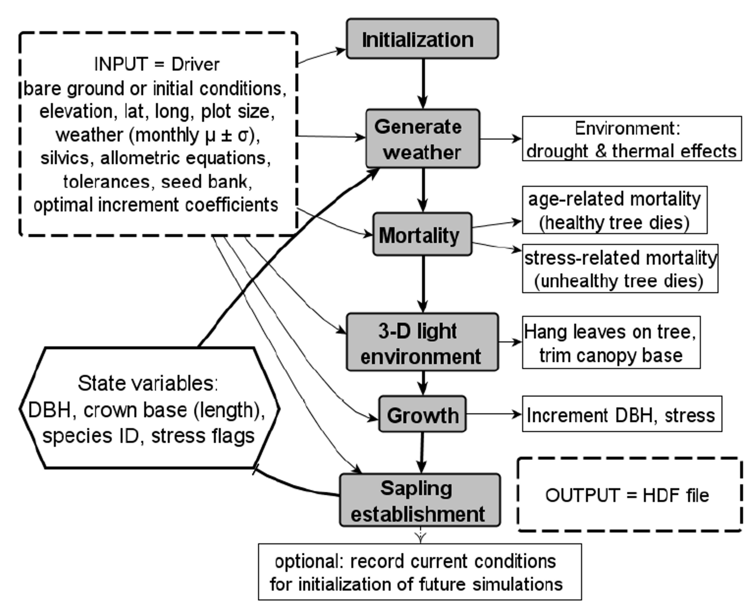
Introduction



In the TTE, the spatial distribution of boreal forest cover and soil profile transition characterizing the Taiga-Tundra Ecological Transition Zone is experiencing an alarming transformation. Permafrost thaw and climate feedback mechanisms remain critical drivers of ecosystem imbalance, seasonality variability, carbon cycling disruption, and increased localized warming in this region.

Materials

The Bonan-derived permafrost subroutine modular upgrades within the SIBBORK-TTE modeling framework coupled with CALM field studies during validation jointly support the monitoring and forecasting precision of *permafrost thaw depth/active layer thickness* dynamics within the TTE ecosystems. Utilizing a TTE site for reference (Brooks02-Brooks Range), we validated site-specific model simulations with four CALM in-situ field observations (Chandalar Shelf, Old Man, Toolik1km, ToolikMAT).



SOILGRIDS MERRA-2 GMAO WCRP CMIP6

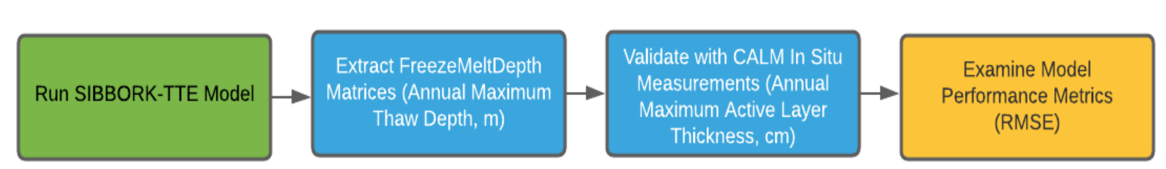
CALM Circumpolar Active Layer Monitoring

SIBBORK-TTE Model CMIP6 Projections (1980-2100):

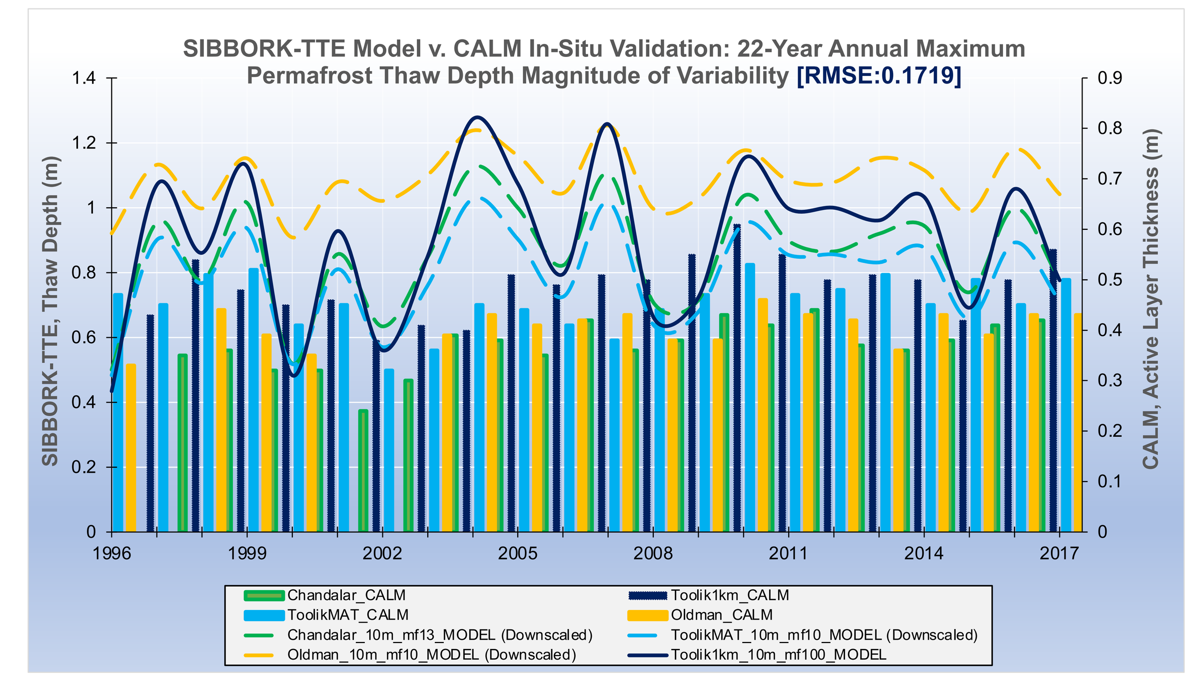
- SIBBORK-TTE Driver Files: MERRA-2 and SoilGrids-derived real climate and soil data integration ([1980-2017]) followed by the instantiation of a CMIP6-derived warming climate function with monthly surface temperature and precipitation metrics (mean, standard deviations, and average seasonal rate of change [slope]; 2018-2100)
- CMIP6.ScenarioMIP.CNRM-CERFACS.CNRM-CM6-1-HR

Methodology

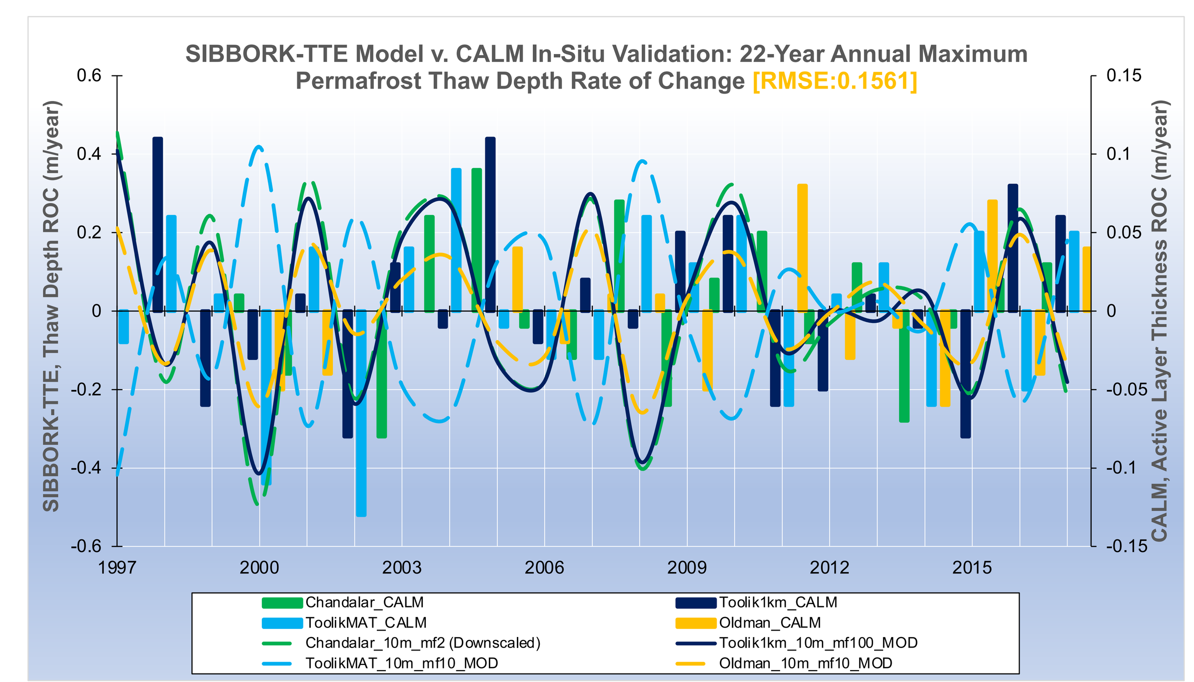
SIBBORK-TTE validation provides verification of current and future model projections necessary for improving our understanding of landscape vulnerabilities, ecosystem change and response patterns, and carbon-climate feedbacks across varying spatiotemporal regions in the TTE.



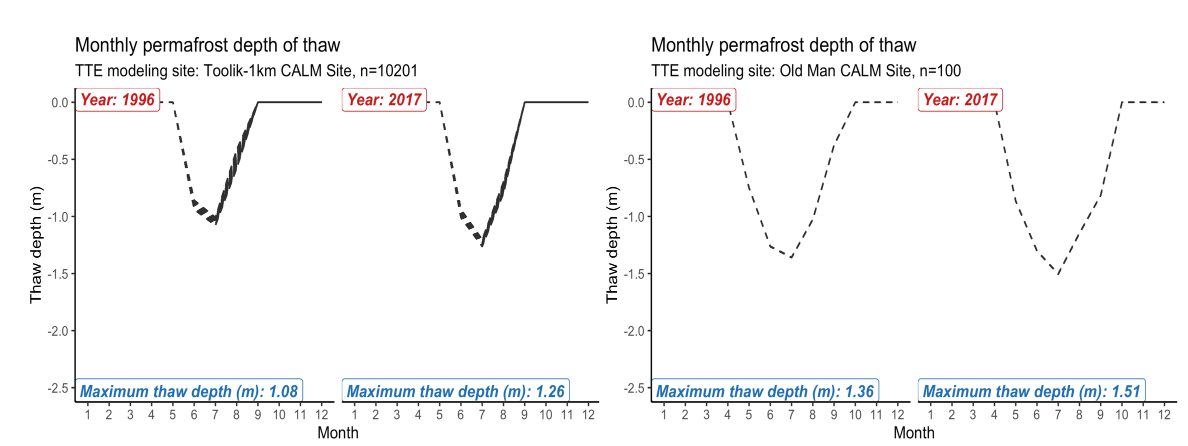
Results



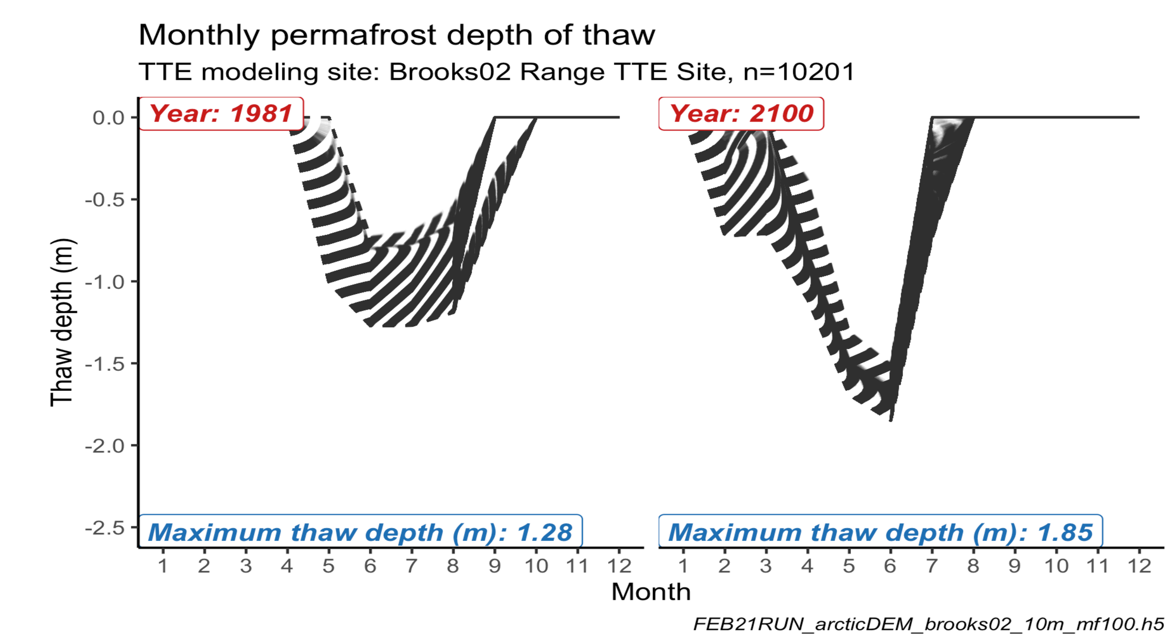
Magnitude of annual maximum permafrost thaw (thaw depth [SIBBORK-TTE], active layer thickness [CALM])



Rate of Change in annual maximum permafrost thaw (thaw depth [SIBBORK-TTE], active layer thickness [CALM])



Conclusions and Future Research

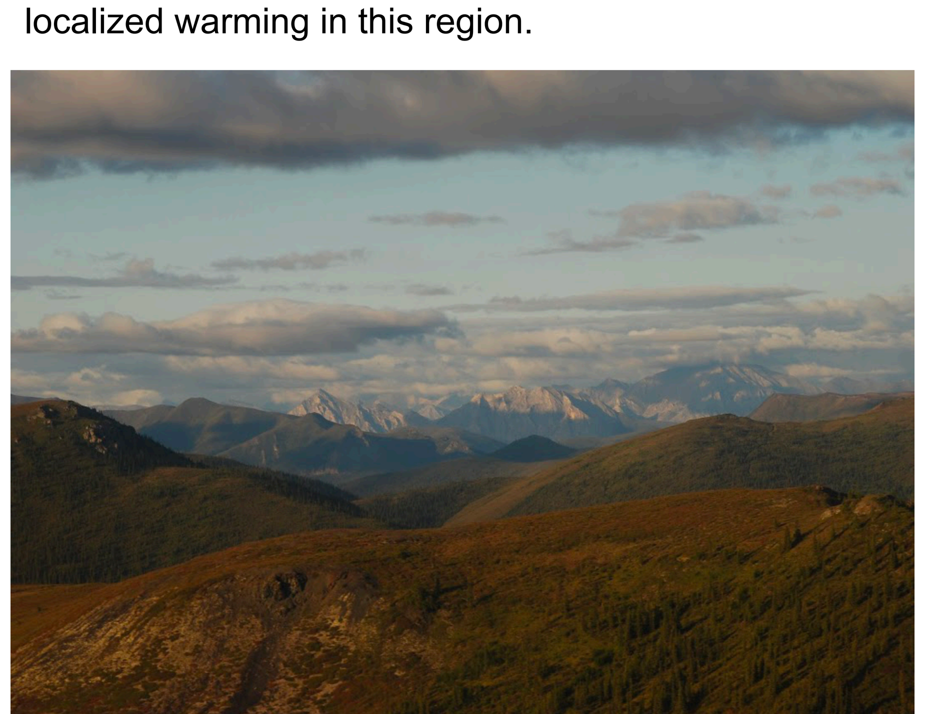


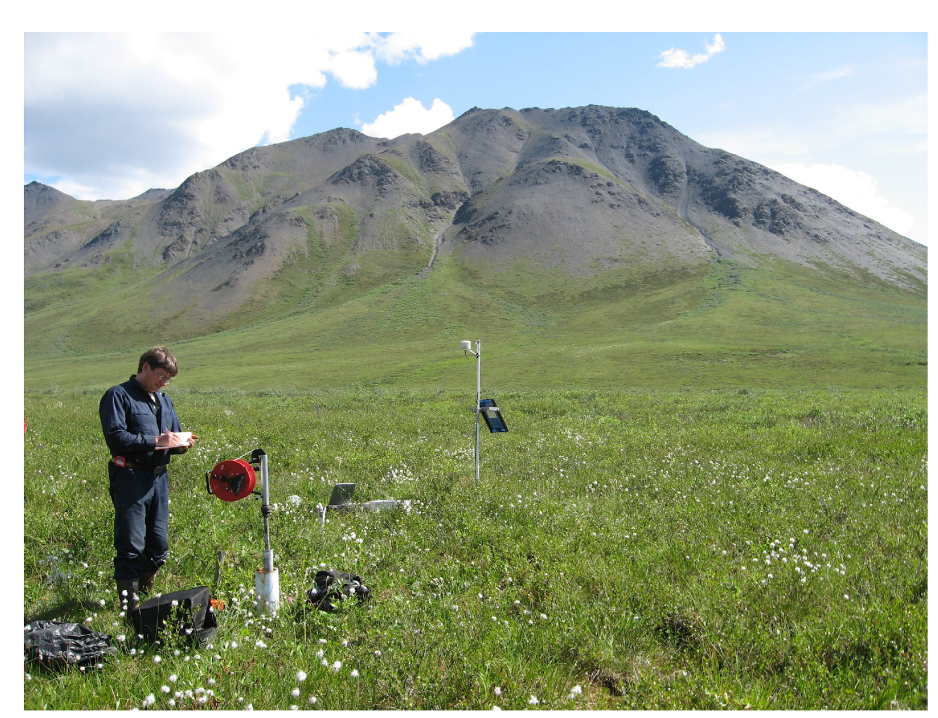
As indicated by the bi-decadal CALM-validated annual plots (1996-2017) and 120-year CMIP6-integrated projections (2018-2100), seasonality disturbance is evident. The deepening, broadening, and shifting of the growing season facilitates more opportunity for rapid freeze-thaw kinetics and increased permafrost thaw. In addition to spatial scaling corrections and microtopographic disparities, global climate forcing kinetics and site-specific causal feedbacks such as biogeochemical factors and vegetation classification appear to play a critical role in annual active layer depth variability, thaw subsistence, water infiltration and mineral dislocation, localized warming, and carbon cycling disruption. Further study of belowground dynamics, near-surface geophysics, and hydrogeochemical factors between sites may help identify specific drivers of permafrost dynamics and classify the spatiotemporal changes in soil water content and vegetation distribution patterns. Future advancements will include adopting higher spatially-resolved imagery as well as developing robust ML/AI-applied pattern recognition multi-dimensional earth system database architecture and deliverable products (Soil-Ecosystem-Carbon-Climate Nexus Database, SECCN; Ecosystem Response Maps, ERMs) to further validate and enhance the modeling framework, current and future simulations, and a better understanding of a fragile, dynamic, and complex domain.

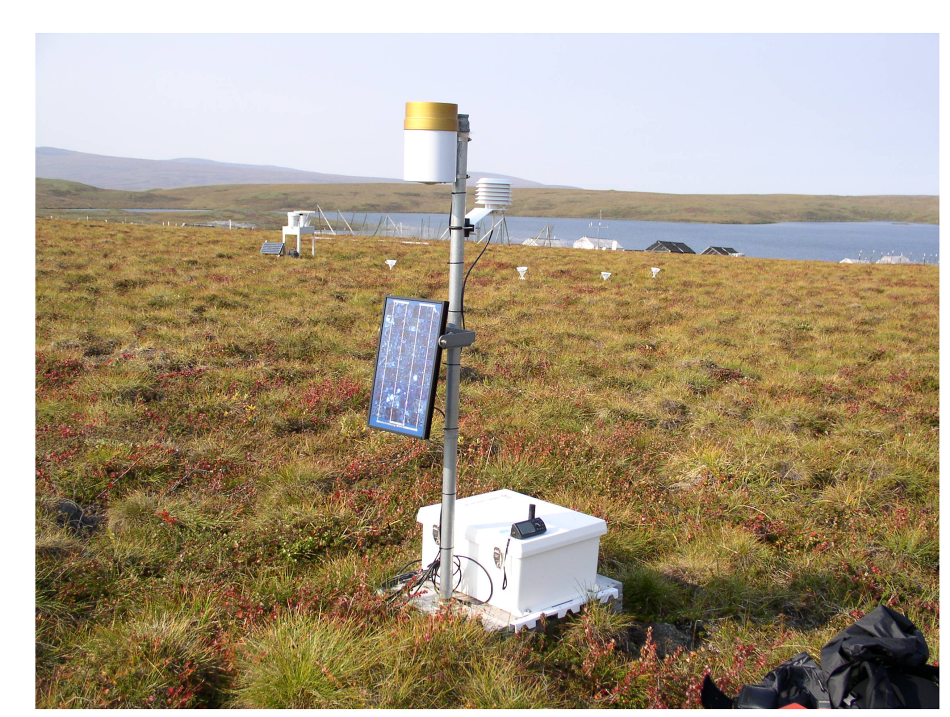
Literature Cited

Bonan, G.B., 1989b. A computer model of the solar radiation, soil moisture, and soil thermal regimes in boreal forests. Ecological Modelling, 45(4), pp.275-306.

Gay, B., Armstrong, A., Montesano, P., Osmanoglu, B., Ranson, K., and Epstein, H. Examination of Current and Future Permafrost Dynamics Across the North American Taiga-Tundra Ecotone, Journal Article, 2021, Earth and Space Science Open Archive, doi:10.1002/essoar.10505667.2







Sites of Interest (from left to right): Brooks02 (Mountainous Trees/Shrubs, TTE), Old Man (Flat Trees/Shrubs, CALM), Chandalar Shelf (Mountainous Shrubs, CALM), Toolik1km (Flat Shrubs, CALM), ToolikMAT (Flat Shrubs, CALM)